Experimental Evaluation of the "Polished Panel Optical Receiver" Concept on the Deep Space Network's 34 meter Antenna

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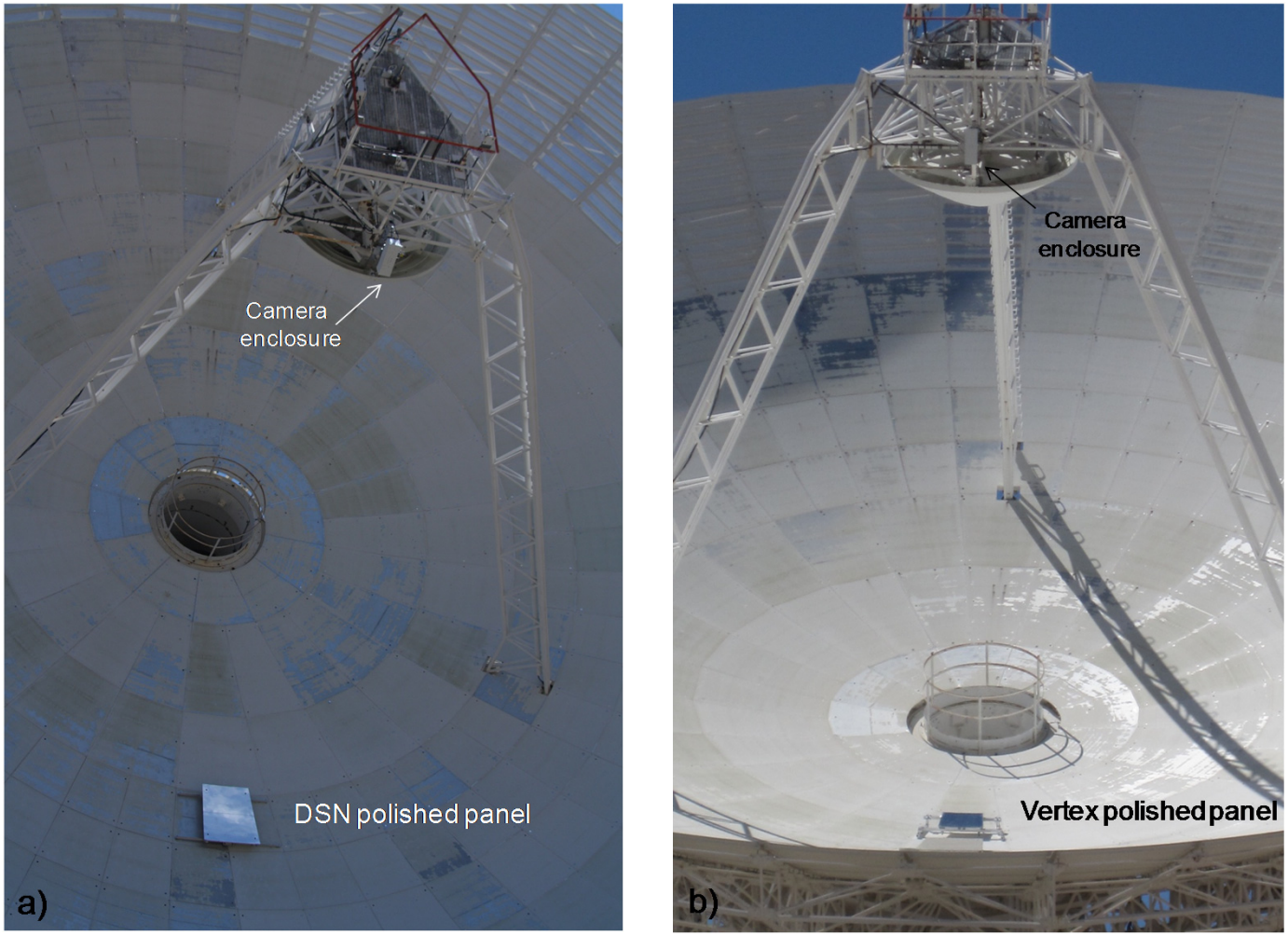
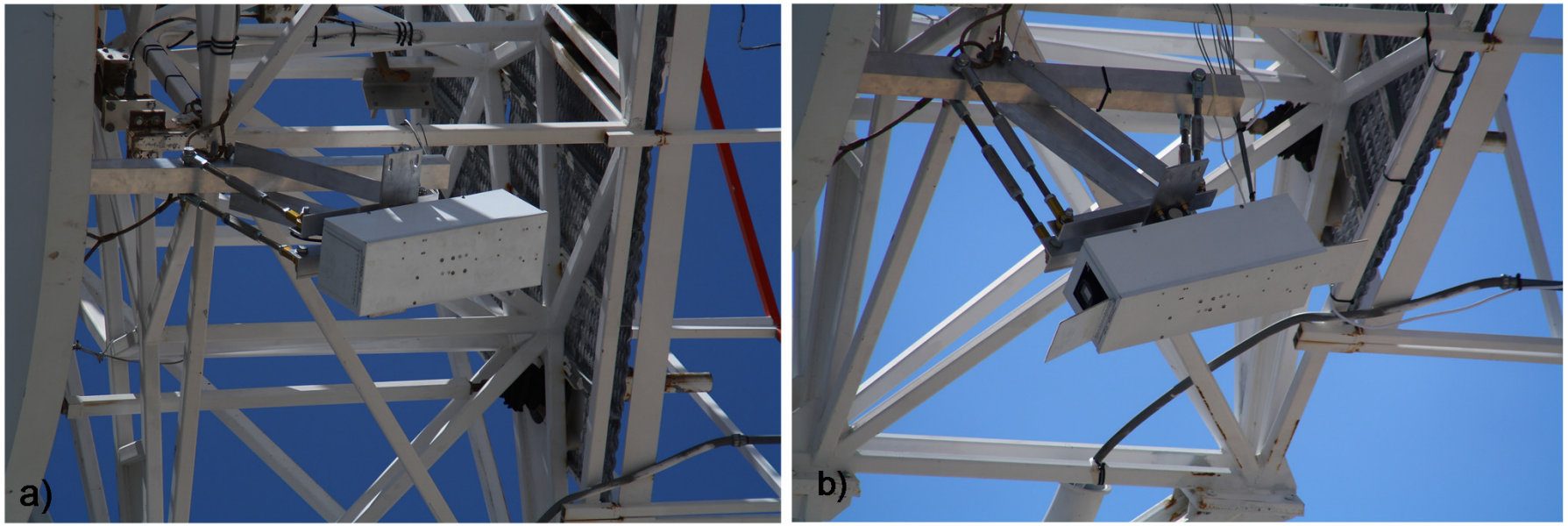
Goal: demonstrate the feasibility of using large aperture "Polished Panel" optical receivers for hybrid RF/Optical deep-space communications via 34-meter DSN antennas

- Installed polished aluminum panels on the main reflector of the 34 meter research antenna at DSS-13, for field evaluation
- Developed and installed a weather-proof remotely controlled camera enclosure on the subreflector support structure
  - Contains a large-sensor camera from Finger Lakes Instruments (FLI)
  - Enclosure and camera are computer controlled from alidade
- Imaged the point-spread-function (PSF) generated by Jupiter
- Developed tracking algorithms based on PSF characteristics
- Evaluated optical communications capabilities based on PSF data

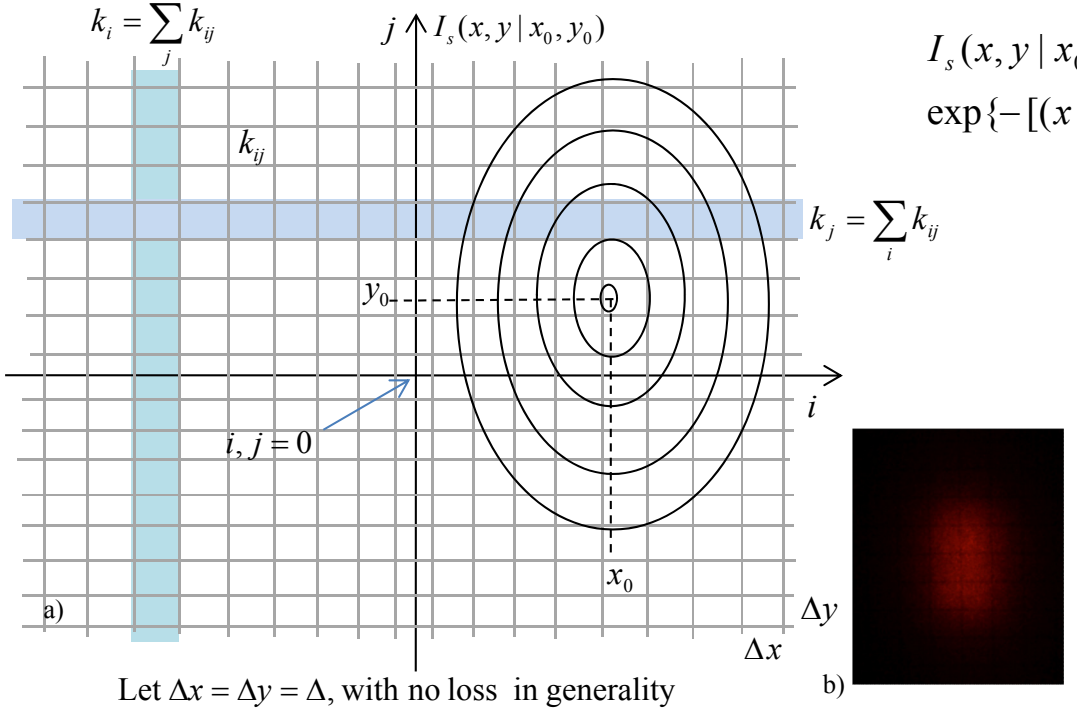


DSN and Vertex Polished Panels mounted on the 34 meter research antenna at DSS-13. a) DSN polished panel mounted on the main reflector, to help establish weather and dust resistance; b) Vertex polished panel mounted on the main reflector, closer to the center.



Remote controlled camera enclosure: a) normally closed configuration; b) open configuration used for data-gathering.

Mathematical model of Focal-Plane Intensity Distribution



Let $\Delta x = \Delta y = \Delta$, with no loss in generality

$$I_s(x, y \mid x_0, y_0) = I_s (2\pi \sigma_s^2)^{-1} \times$$
$$\exp\{-[(x - x_0)^2 / 2\sigma_x^2 + (y - y_0)^2 / 2\sigma_y^2]\} \quad \text{watts/cm}^2$$

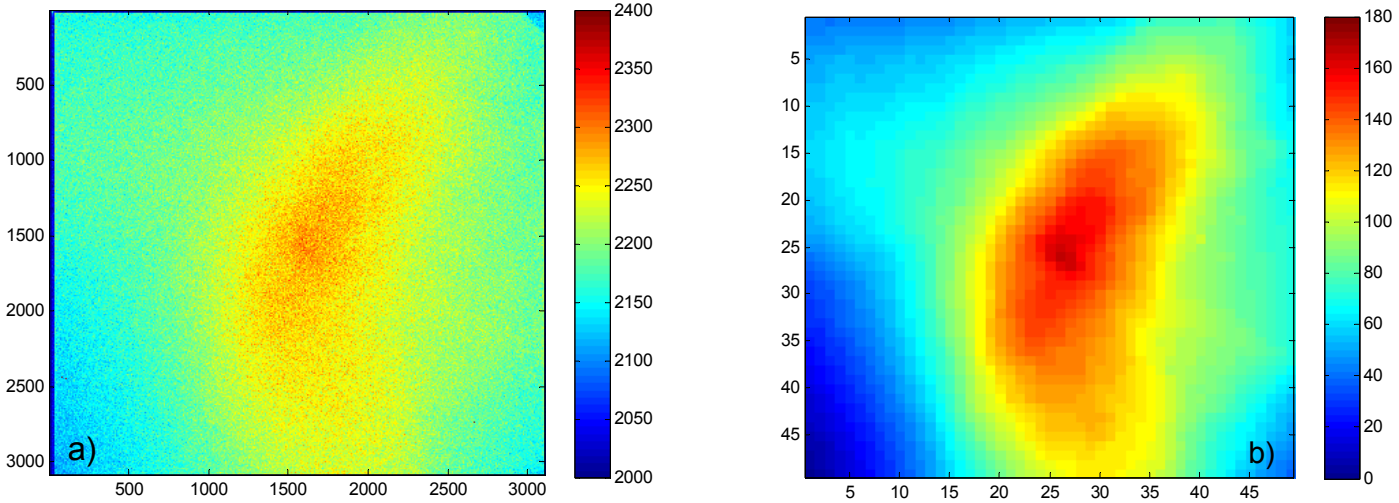
$$\lambda_s(i, j \mid x_0, y_0) = \int_0^T P_s(i, j \mid x_0, y_0)\, dt$$
$$\cong T\Delta^2 I_s(i\Delta, j\Delta \mid x_0, y_0)$$

$$p(k_{ij} \mid x_0, y_0) = [\lambda_s(i, j \mid x_0, y_0)]^{k_{ij}} \times$$
$$\exp[-\lambda_s(i, j \mid x_0, y_0)] / k_{ij}!$$

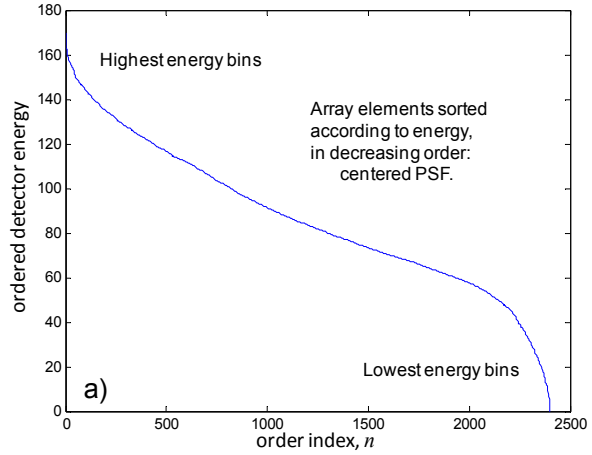
a) Focal-plane model of pixel array, and elliptical PSF with pointing offsets , motivated by: b) experimentally determined point-spread function (PSF) for the high-quality Vertex panel, photographed on the JPL mesa test range.

$$p(\mathbf{k} \mid x_0, y_0) = \prod_{i,j} [\lambda_s(i, j)]^{k_{ij}} \exp[-\lambda_s(i, j)] / k_{ij}!$$

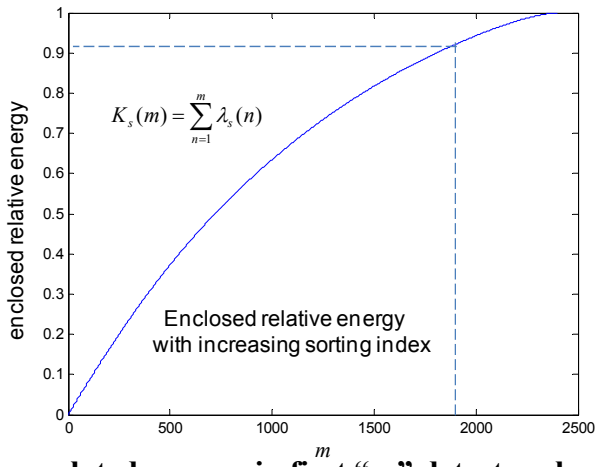
Communications Performance: Experimentally Obtained PSF



Centered PSF recorded with FLI camera: a) original 10 mega-pixel resolution showing speckle pattern; b) 60X60 binned image emphasizing the spatially averaged structure of the point-spread-function.



Pixels sorted according to energy

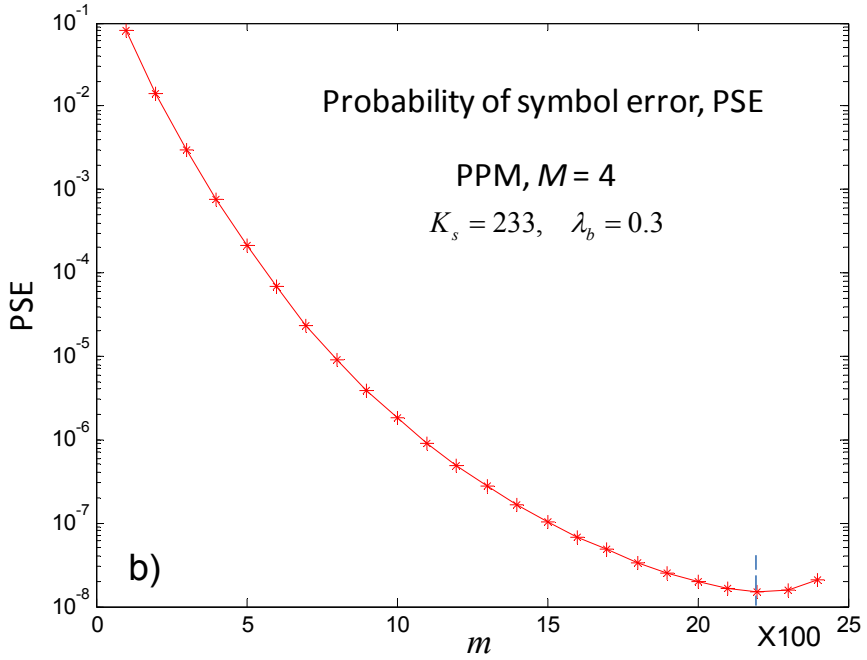


Accumulated energy in first "m" detector elements

Communications Receiver Performance, PPM Signals

$$P_M^l(C) \geq \sum_{k=1}^{\infty} \frac{\left(K_s(m)+K_b(m)\right)^k}{k!} \exp\left[-\left(K_s(R)+K_b(R)\right)\right] \times \left\{ \sum_{j=0}^{k-1} \frac{\left(K_b(R)\right)^j}{k!} \exp\left[-\left(K_b(R)\right)\right] \right\}^{M-1}$$

$$P_M^u(E) \equiv 1 - P_M^l(C) \geq P_M(E) \cong P_M(E)$$

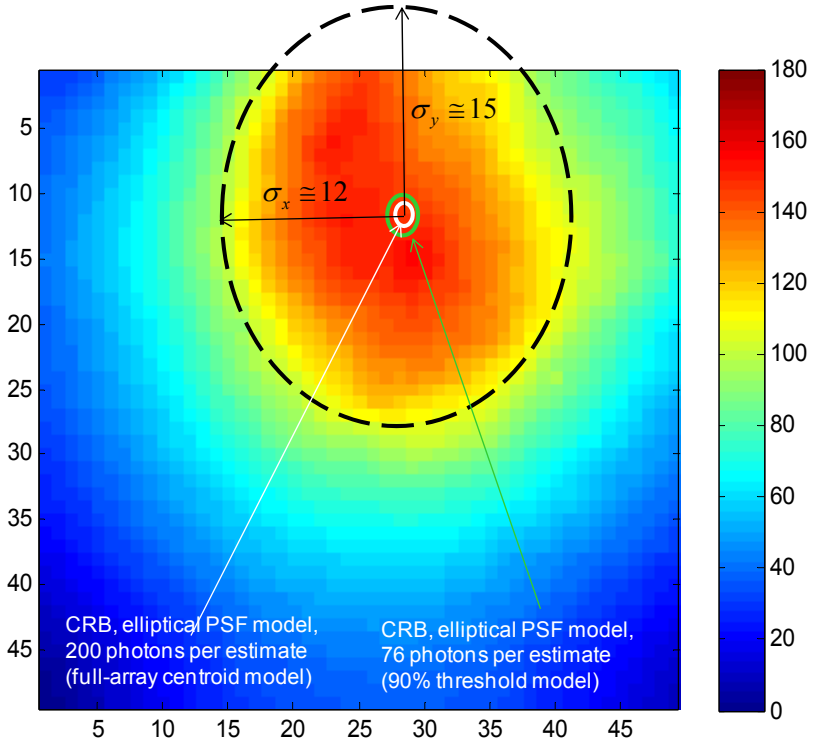


$$K_s(m) = \sum_{n=1}^{m} \lambda_s(n)$$

$$K_b(m) = m\lambda_b$$

$$P_M(C) \cong \int_{-\infty}^{\infty} dy\, Gsn[K_s(m)+K_b(m), y] \times \left[\int_{-\infty}^{y} dx\, Gsn[K_b(m), x] \right]^{M-1}$$

Probability of symbol error (PSE) with optimal "1, 0" mask, with background counts of 0.3 photons per slot per bin.



Estimate of the Cramer-Rao bound for the unmodified and modified threshold algorithms: elliptical PSF with minor axis ~12 bins, major axis ~16 bins.

Centroid Estimator Performance

Several Centroid-estimation algorithms were developed and evaluated:

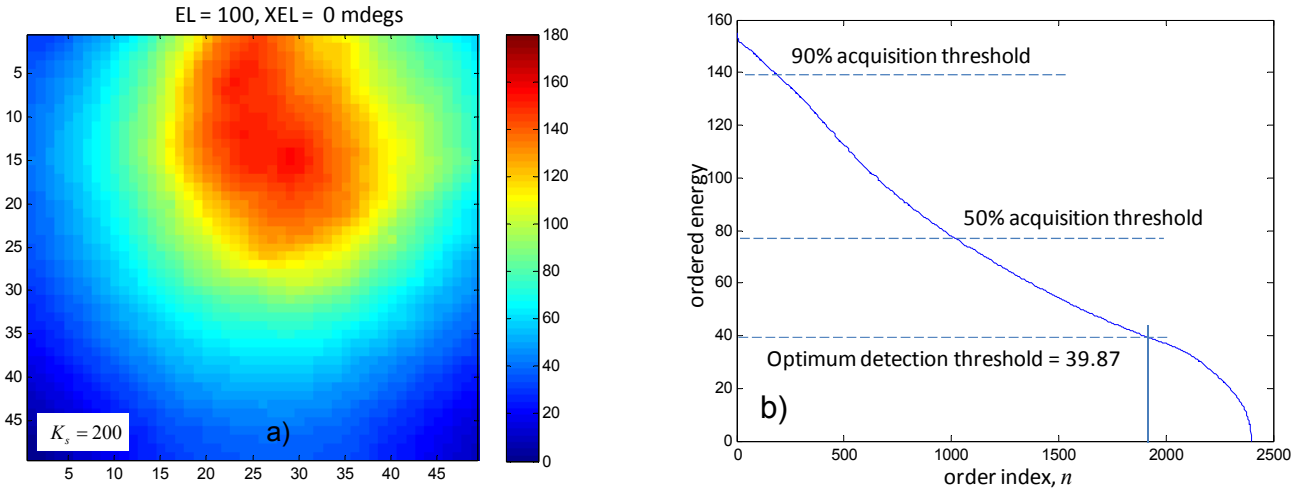
- without masking, using the entire array
- with various (1,0) masks defined as:
  - optimal detection mask
  - top 50% (order index)
  - top 90% (order index)

Cramer- Rao bound: Centroid estimation algorithms

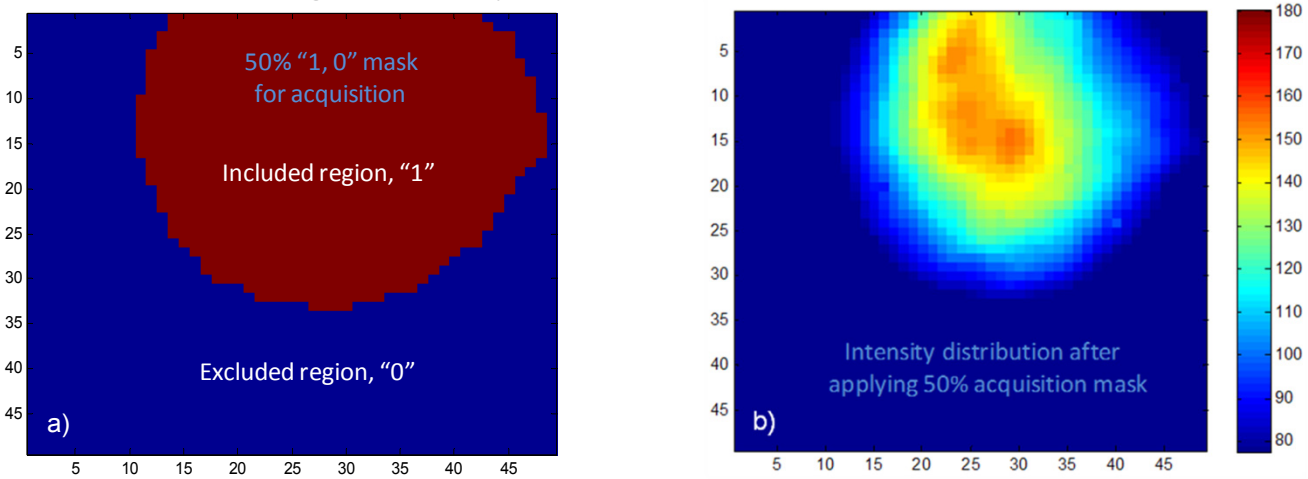
$$\mathrm{var}(\hat{x}_0 - x_0) \geq \left\{ -E\left[-\sum_i \sum_j k_{ij} / \sigma_x^2 \right] \right\}^{-1} = \frac{\sigma_x^2}{\Lambda_s}$$

$$\mathrm{var}(\hat{y}_0 - y_0) \geq \left\{ -E\left[-\sum_i \sum_j k_{ij} / \sigma_y^2 \right] \right\}^{-1} = \frac{\sigma_y^2}{\Lambda_s}$$

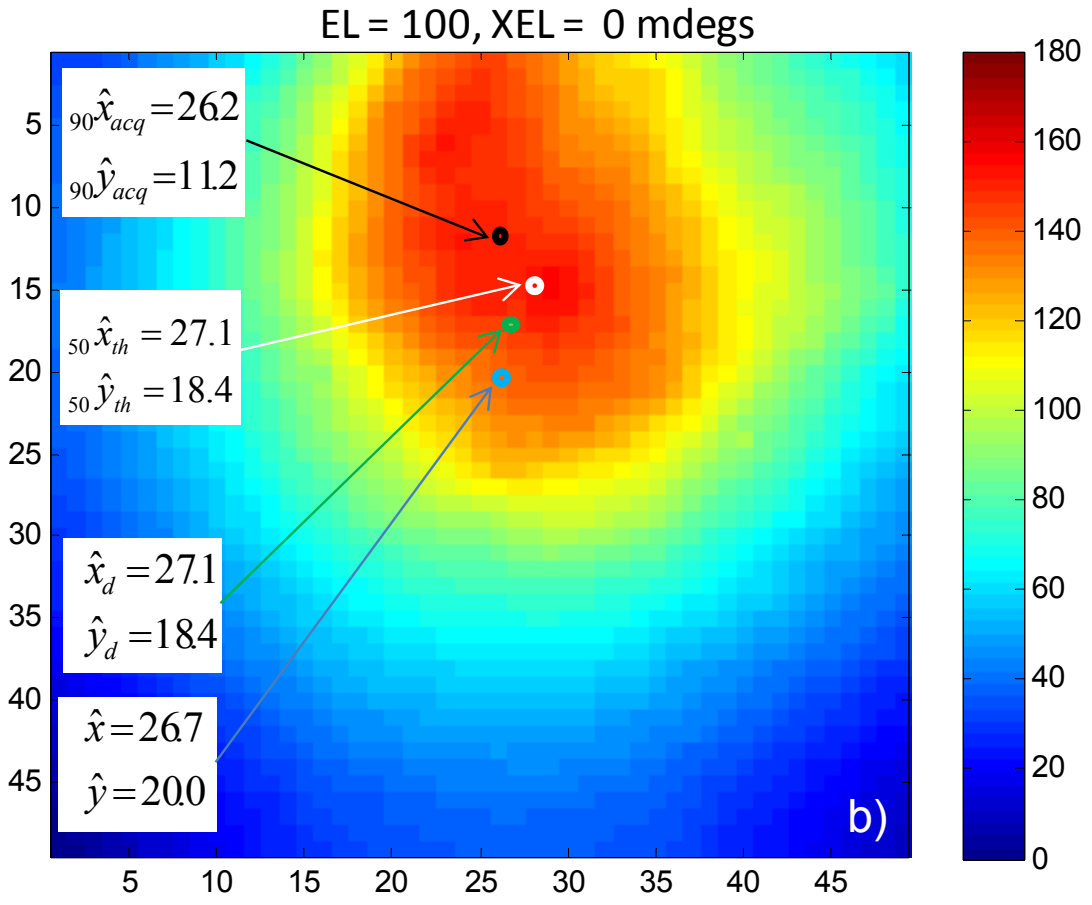
$$\sigma_x \equiv \sqrt{\mathrm{var}(\hat{x}_0 - x_0)} \qquad \sigma_y \equiv \sqrt{\mathrm{var}(\hat{y}_0 - y_0)}$$



a) Initial PSF before centering, with 100 mdeg pointing error in elevation; b) Detector elements ordered according to intensity, as a function of the order index "*n*".



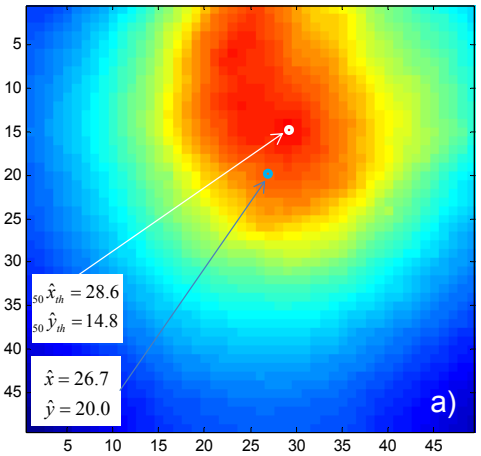
a) Simple "1, 0" mask obtained by including only those elements with order index less than 1900; modified intensity distribution after the detection mask is applied.



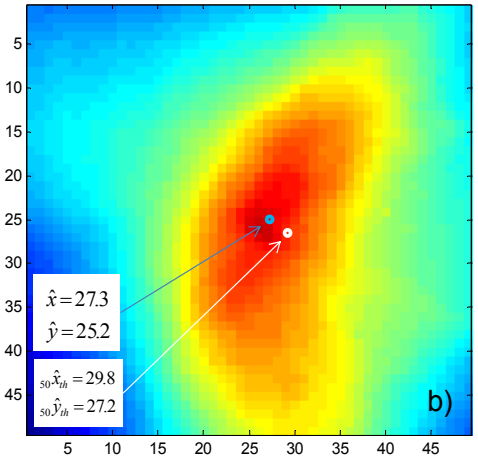
PSF center estimates obtained with the original centroid algorithm, detection-mask (1,0) algorithm, 50% and 90%-threshold (1,0) algorithms.

Response to Offsets and Centroid Algorithm Performance

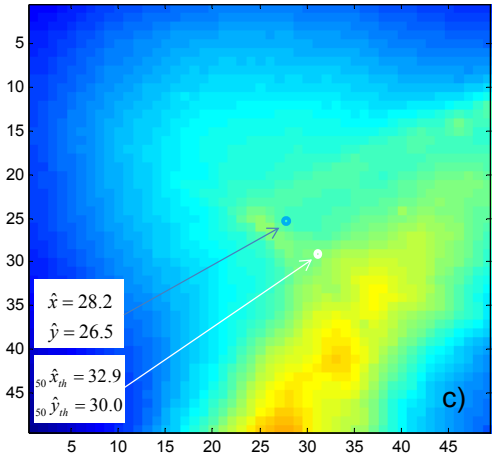
Original and 90%-threshold estimates, with elevation and cross-elevation offsets:



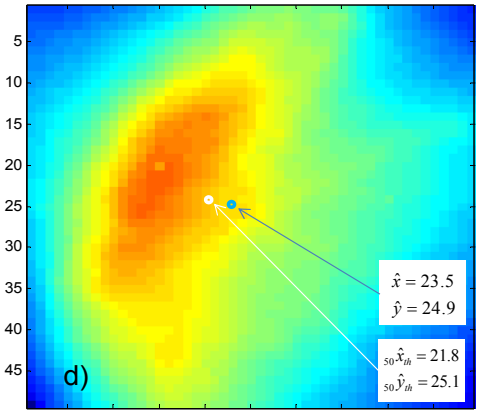
a) EL = 100 mdeg



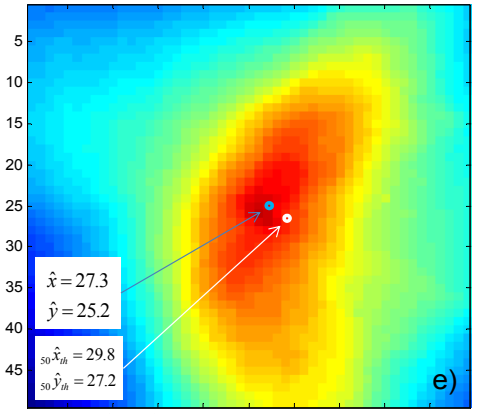
b) EL = 0 mdeg (centered)



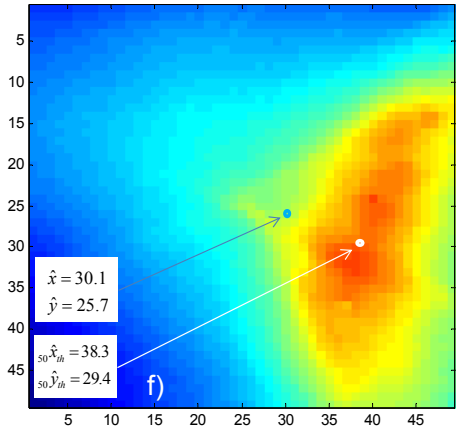
c) EL = -100 mdeg



d) XEL=50 mdeg



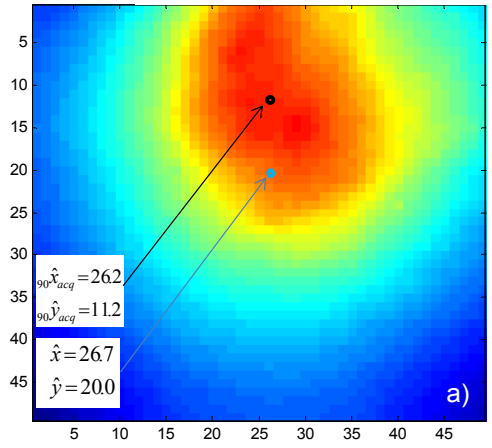
e) XEL = 0 mdeg (centered)



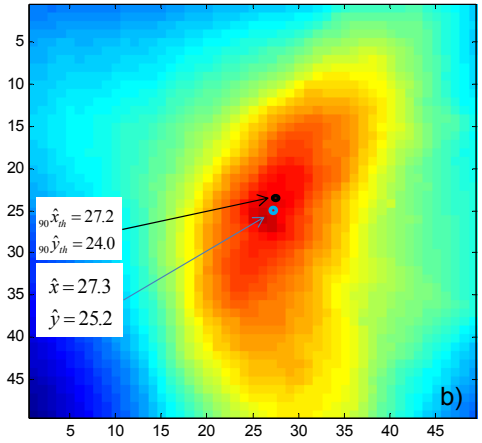
f) XEL=-50 mdegs

Response to Offsets and Centroid Algorithm Performance

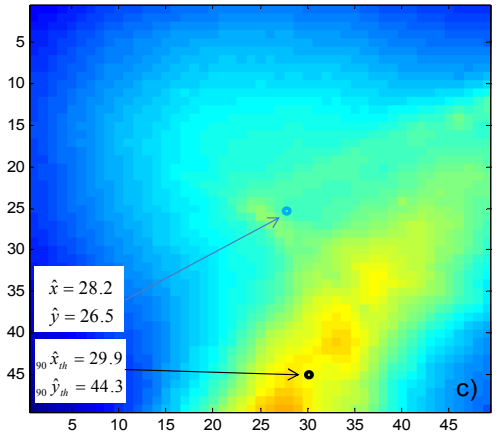
Original and 90%-threshold estimates, with elevation and cross-elevation offsets:



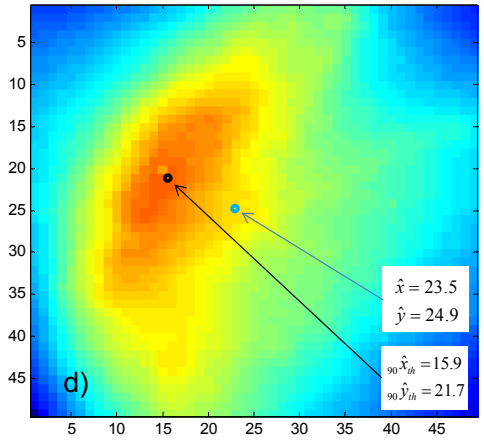
a) EL = 100 mdeg



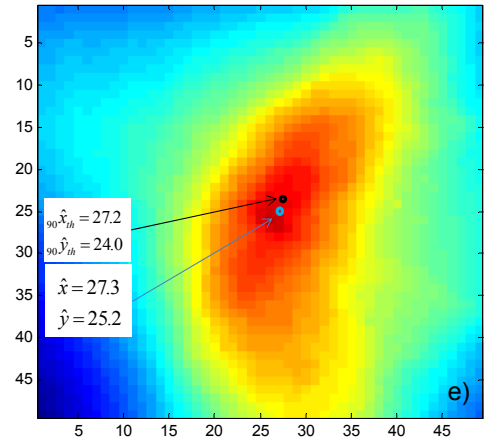
b) EL = 0 mdeg (centered)



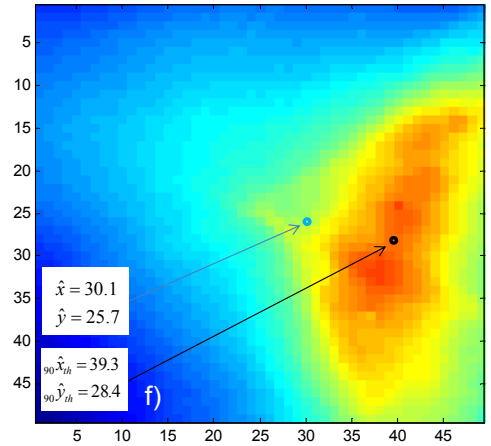
c) EL = -100 mdeg



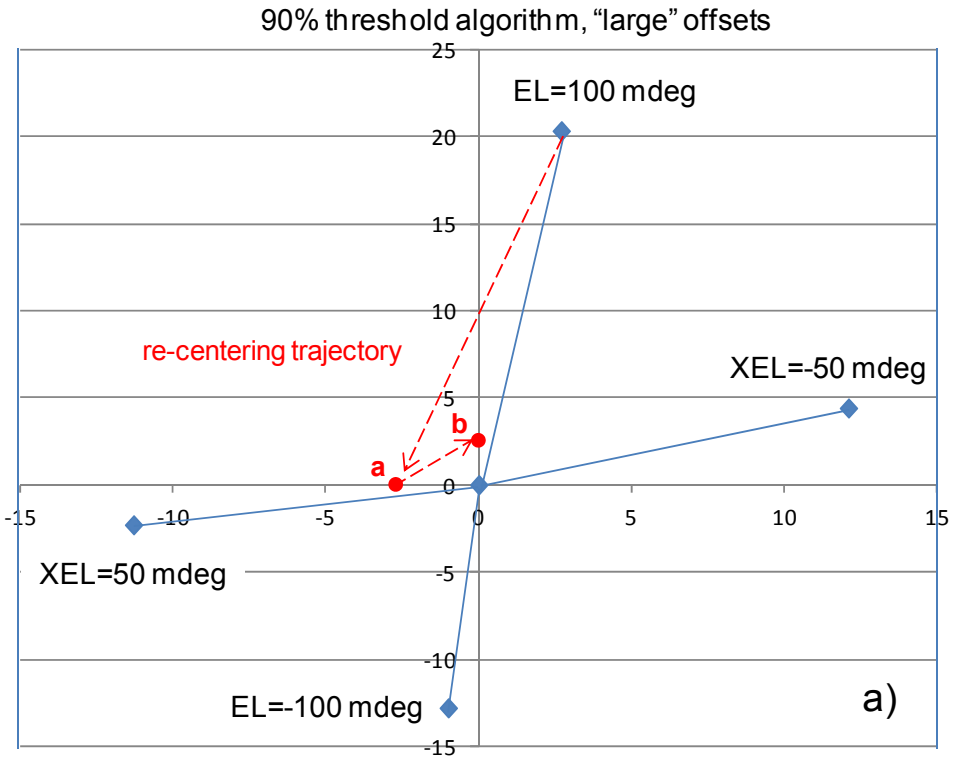
d) XEL=50 mdeg

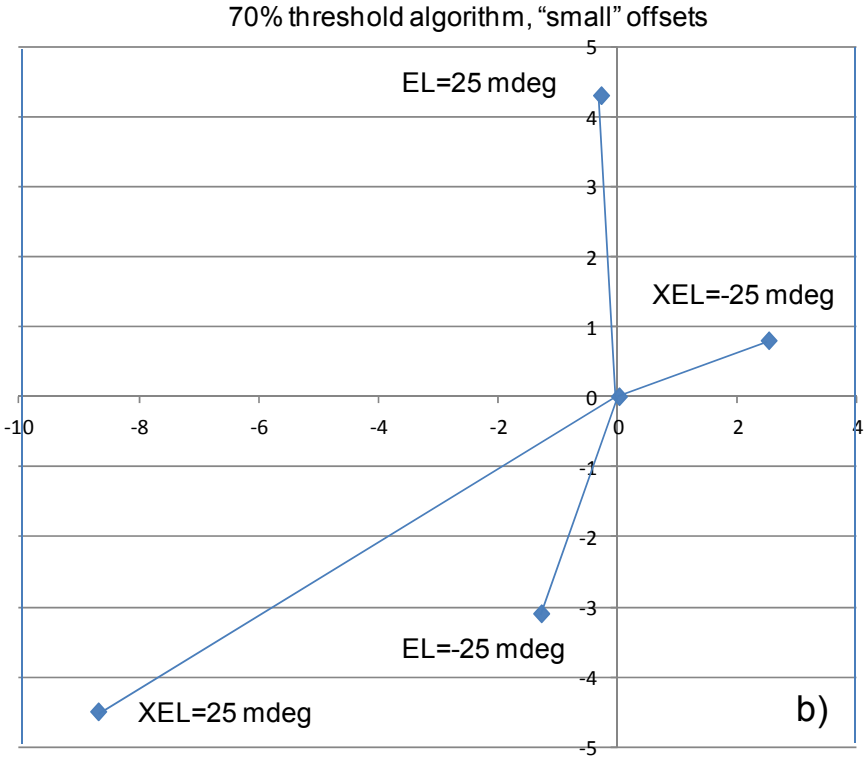


e) XEL = 0 mdeg (centered)



f) XEL=-50 mdegs





Response of a) 90%-threshold algorithm to "large" offsets, and b) 70%-threshold algorithm to "small" offsets, in the (XEL, EL) plane.

	$\hat{x}$	$\hat{y}$	${}_{70}\hat{x}_{th}$	${}_{70}\hat{y}_{th}$	${}_{90}\hat{x}_{th}$	${}_{90}\hat{y}_{th}$
center	27.2	25.1	29.8	27.2	27.3	24.0
Δ – center	0	0	0	0	0	0
EL=25	-0.5	-1.1	-1.3	-3.1	-0.3	-1.9
EL=-25	0.0	0.6	-0.3	4.3	1.0	4.8
XEL=25	-3.0	-1.5	-8.7	-4.5	-4.4	-2.3
XEL=-25	0.0	-0.8	2.5	0.8	5.6	3.6

Summary of center estimates, and response to "small" offsets relative to center for the original, 70% and 90%-threshold centroid algorithms.